

N O T I C E

THIS DOCUMENT HAS BEEN REPRODUCED FROM
MICROFICHE. ALTHOUGH IT IS RECOGNIZED THAT
CERTAIN PORTIONS ARE ILLEGIBLE, IT IS BEING RELEASED
IN THE INTEREST OF MAKING AVAILABLE AS MUCH
INFORMATION AS POSSIBLE



Technical Memorandum 80694

THE 1979 X-RAY OUTBURST OF CEN X-4

(NASA-TM-80694) THE 1979 X-RAY OUTBURST OF
CEN X-4 (NASA) 25 p HC A02/MF A01 CSCL 03B

N80-26235

Unclassified
G3/90 22947

L. J. Kaluzienski
S. S. Holt
J. H. Swank

MAY 1980

National Aeronautics and
Space Administration

Goddard Space Flight Center
Greenbelt, Maryland 20771



THE 1979 X-RAY OUTBURST OF CEN X-4

L.J. Kaluzienski¹, S.S. Holt, and J.H. Swank

Laboratory for High Energy Astrophysics
NASA/Goddard Space Flight Center
Greenbelt, Maryland 20771

ABSTRACT

In late spring 1979 the "classical" transient X-ray source Cen X-4 underwent its first major outburst since its initial discovery in 1969. We present X-ray observations of this event obtained with the Ariel 5 All-Sky Monitor. The flare light curve exhibits a double-peaked maximum at a level of ~ 4 times the Crab nebula, and its duration and characteristic decay time scale are the shortest yet observed from the class of "soft" X-ray transients. We estimate a total X-ray output of $\sim 3 \times 10^{43}$ ergs, a factor of ~ 20 less than that of the 1969 outburst. In addition, evidence is found for a regular modulation of the flux during the decline phase at a period of 8.2 ± 0.2 hours. The existing data are consistent with a source model involving episodic mass exchange from a late-type dwarf onto a neutron star companion in a relatively close binary system.

Subject headings: stars: binaries - stars: individual - X-Rays:
binaries - X-Rays: bursts

¹Now at NASA Headquarters, Washington, D.C.

I. INTRODUCTION

An outburst from the long-dormant transient X-ray source Cen X-4 was detected in 1979 May with the All-Sky Monitor (ASM) on Ariel 5 (Kaluzienski and Holt 1979 b,d). The only other recorded X-ray outburst from this object was observed with the Vela 5 satellites in 1969 July, when the source reached a peak intensity of $\sim 5 \times 10^{-7}$ erg cm $^{-2}$ s $^{-1}$ (3-12 keV) and remained bright ($S \gtrsim 0.01 S_{\text{max}}$) for more than two months (Evans, Belian, and Conner 1970). The absence of the source in the HEAO-A2 sky survey during 1977-1978 (Marshall 1979) yields an upper limit to the quiescent flux level of $\sim 1 \times 10^{-11}$ erg cm $^{-2}$ s $^{-1}$ (2-10 keV), implying a variability of $\gtrsim 5 \times 10^4$. Cen X-4 is also an X-ray burst source, as evident from observations of an intense Type I burst during the decline of the present outburst (Oda 1979b; Matsuoka et al. 1980) and an unusually long and bright burst-like event prior to the 1969 episode (Belian, Conner, and Evans 1972). UV observations conducted approximately one week after onset of the 1979 outburst revealed the presence of a star which had brightened by at least six magnitudes over the level observed in the Palomar Observatory Sky Survey ($m_V \gtrsim 19$; Canizares, McClintock, and Grindlay 1979a,b) at a position consistent with the revised Vela 5 X-ray location (Terrell et al. 1979). The object was also observed during outburst at UV wavelengths with the IUE satellite (Wu 1979) and in the radio band with the Very Large Array (Hjellming 1979).

In Section II we present the All-Sky Monitor observations of the 1979 episode, including evidence for a source modulation at a period of 8.2 hours. In Section III, these results are discussed in the context of the other existing data on Cen X-4 and the characteristics of the "soft" transients as a class. In Section IV, we interpret the overall source observations in terms of episodic mass exchange in a relatively close, low mass binary system with mass ratio $q \equiv M_x/M_{\text{opt}} \gtrsim 1$.

II. EXPERIMENTAL RESULTS

The All-Sky Monitor (ASM) on Ariel 5 is a wide-field X-ray camera which provides nearly continuous coverage of $\gtrsim 3\pi$ steradians of the sky in the 3-6 keV energy band. The instrument sensitivity is ~ 0.07 and $\sim 0.12 \text{ ph cm}^{-2} \text{ s}^{-1}$ ($1 \text{ photon cm}^{-2} \text{ s}^{-1} \approx 1.3 \times 10^{-8} \text{ erg cm}^{-2} \text{ s}^{-1}$ (2-6 keV)) for half-day integrations in the fine ($\delta\theta \sim 2^0$) and coarse ($\delta\theta \sim 10^0$) spatial resolution modes, respectively. The temporal resolution is defined by the satellite orbital period of ~ 100 minutes. No spectral information within the nominal 3-6 keV energy window is retained. A detailed description of the ASM is given in Holt (1976).

a. Light Curve

Onset of the present outburst from Cen X-4 occurred between ~ 1100 hrs UT on 1979 May 11 and ~ 0100 hrs UT on May 13, where the uncertainty reflects a gap in all-sky coverage resulting from fine-mode observations of the Norma-Circinus region during that interval. The source brightened rapidly from a level of $\sim 0.8 \text{ ph cm}^{-2} \text{ s}^{-1}$, attaining a flux of $\sim 5 \text{ ph cm}^{-2} \text{ s}^{-1}$ early on May 17. The phase of maximum light lasted until \sim May 24, when an abrupt decline (e-folding time $\tau \sim 3$ days) commenced, the flux dropping below the ASM threshold by \sim June 10. ASM coverage of the Centaurus region during 1974 October - 1979 April produced no significant source detections, thereby excluding (except for occasional brief gaps in coverage) outbursts of peak flux $\gtrsim 0.2 \text{ ph cm}^{-2} \text{ s}^{-1}$ during that interval.

The ASM light curve of this episode is shown in Figure 1. We note several interesting aspects of the 1979 event apparent in this Figure: (1) the light curve exhibits many of the characteristic features observed from other transients, including a pre-cursor peak (or more appropriately, a "pre-maximum halt"; see May 14), a double-peaked maximum (May 16-21), secondary maxima or plateaus during the decline phase (e.g., May 22-24, 28-30), and the absence of eclipse-like modulation; (2) the presence of significant, apparently random variations on time scales down to the limiting instrumental resolution, particularly during

maximum light; and (3) the lower peak flux and shorter duration relative to the 1969 event (S_{\max} (1979) $\sim 0.2 S_{\max}$ (1969); $T_{.01}$ (1979) $\sim 0.4 T_{.01}$ (1969)), where $T_{.01} \equiv$ time to reach 0.01 S_{\max}). We also note the similarity of the light curve to that of H1705-25 (Nova Ophiuchi 1977). Except for a substantial difference in the time scales of the final decay ($T_{.01} \sim 1$ month and > 5 months for Cen X-4 and H1705-25, respectively), the characteristics of the 1979 flare of Cen X-4 (including rise-time, precursor/pre-maximum halt, double-peaked maximum, duration of maximum light, and rate of initial decline) are strikingly similar to those of H1705-25 (cf. Figure 1, Watson, Ricketts, and Griffiths 1978).

b. Periodic Behavior

A search for a possible underlying periodic modulation was conducted by application of the standard epoch-folding technique to the data of Figure 1. Linear decay trends (obtained via visual fits to the data) over the intervals corresponding to May 24-26, May 27-28, and May 29-June 2 were subtracted from the data and a d.c. component of $1.6 \text{ ph cm}^{-2} \text{ s}^{-1}$ added to the residuals. The entire decline phase data sample (May 24-June 2) was then folded in 7 bins over trial periods in the range $P=0.1 - 5$ days, and the resulting χ^2 distribution (vs. the assumption of source constancy) inspected for deviations above the average level. As shown in Figure 2, a relative maximum in the χ^2 distribution is observed in the vicinity of $P_0 = 0.3415^d$ ($\sim 8.2^h$), and weaker maxima are evident at the $n=2$ and 3 multiples of this period. No deviation is apparent at $P_0/2$ (0.1708^d). This latter period is close to the 4.8 hour (0.199^d) period of Cyg X-3, which is clearly detectable with the ASM over longer intervals (but with a lower average flux; cf. Holt et al. 1979). In Figure 3a, the detailed variation of χ^2 near 0.3415^d is shown. We note that the width of the χ^2 maximum is commensurate with that expected from a true modulation at this period over the data interval sampled (~ 9 days). The shape of the modulation is shown in the folded light curve of Figure 3b, and is consistent with either a sinusoidal or "dip"-like variation.

The reality of the 8.2^h effect was investigated in several ways. The data in Figure 1 during the phase of maximum light (May 16-24) were folded in the same fashion as the decline phase data. In addition to the higher average level of χ^2 , several peaks in the vicinity of 8.2 hr are evident but inconsistent with this period. We do not consider this irreconcilable with the earlier result, however, primarily because of the larger short- and long-term fluctuations evident during the stage of X-ray maximum. The likely significant variation in physical conditions at the source corresponding to the peak and decay stages could also account for the differing results. To test for a possible systematic effect, temporal analyses of single-orbit data from both the Crab nebula and Aql X-1 over similar data intervals were examined for evidence of modulation at the suspected period. Neither of these sources exhibited a significant effect in the vicinity of 8.2 hrs. Finally, the individual data points (decay-trend subtracted) were plotted modulo the 8.2 hour period and visually inspected. No obvious artifacts of the subtraction procedure which might contribute to the observed effect were evident. Using the FWHM of the χ^2 peak as an indicator of the uncertainty in the period determination and taking the center of the minimum bins as phase zero, we obtain values of $P_0 = 0.3415^d \pm 0.008^d$ and $T_0 (\phi = 0.0) = \text{JD } 2,442,013.52 \pm 0.04$. The amplitude of the modulation, expressed as a percentage of the mean flux value of the decline phase data ($\sim 1.6 \text{ ph cm}^{-2} \text{ s}^{-1}$), is $\sim 10\%$ (peak to mean) for a sinusoidal modulation. Due to the marginal nature of this result, we claim only that our data provide an indication of a possible source modulation at 0.3415^d , and note that further observations are required to determine its reality.

III. DISCUSSION

a. Comparison with Other Observations

In addition to the continuous X-ray monitoring of the outburst provided by the ASM, extensive X-ray coverage of the source was obtained with the HAKUCHO satellite commencing on May 28 (see Matsuoka et al. 1980). These observations extend the light curve of the 1979 flare beyond the last positive ASM detections shown

in Figure 1 (~ June 4) through ~ June 11, when a final abrupt decline was observed. Also, an intense ($S \sim 25 S_{\text{crab}}$, 1.5-12 keV), ~10 second burst from the source was detected with the HAKUCHO experiment at $\sim 14^{\text{h}} 09.5^{\text{m}}$ UT on May 31 (Oda 1979b; Matsuoka et al. 1980). As indicated in Figure 1, the burst occurred during the decline subsequent to the small recovery maximum around May 29. No significant deviation in the source flux on time scales long compared to that of the burst is evident in the ASM data during this time.

Extensive coverage of Cen X-4 at optical wavelengths during the outburst was obtained by several observers. As noted by Canizares, McClintock, and Grindlay (1979b), a correlation of the optical and X-ray fluxes (ASM half-day averages) is clearly present over the interval May 19 - June 4, during which time the source declined by approximately two magnitudes from maximum brightness ($m_V = 12.8$). As evident in Figure 1, this corresponds to the period including the interpeak minimum, second maximum, initial decline, and recovery peak. Subsequent optical observations on June 14 and 24 yielded respective B magnitudes of ~ 18 and 18.8 (Seitzer, Smith, and Ross 1979; Canizares, McClintock, and Grindlay 1979b). The decline in optical brightness of ~ 5 magnitudes between May 19 and June 14 is commensurate with the decrease in X-ray intensity during this interval of $\gtrsim 100$ measured with the ASM. The source decline at optical wavelengths apparently slowed significantly during the next month, as the last reported observation on July 15 yielded a B magnitude of ~ 18.5 (Wyckoff 1979). The June 24 and July 15 measurements combined with the observed steep X-ray falloff on \sim June 11 suggests an apparent lag of the optical emission with respect to the X-ray emission in Cen X-4 during the final decline phase. We note the great similarity of the X-ray/optical behavior of Cen X-4 to that of other transients, particularly A0620-00/V616 Mon (=Nova Monocerotis 1975; cf. Kaluzienski et al. 1977b).

Estimates of the ratio of X-ray to optical luminosity (L_X/L_O) at the peaks observed with the ASM are similar to those of several other transients.

The X-ray spectrum obtained by Matsuoka et al. (1980) is consistent with thermal bremsstrahlung emission with temperature $kT = 4.5 - 11$ keV. Assuming a thermal spectrum with $kT \sim 7$ keV, the peak ASM flux of $\sim 5 \text{ ph cm}^{-2} \text{ s}^{-1}$ corresponded to a total X-ray flux $S_x \sim 1.6 \times 10^{-7} \text{ ergs cm}^{-2} \text{ s}^{-1}$. Wu (1979) reported that the reddening is low ($E_{B-V} \sim .015$) and that the UV flux (3100-1100Å) near the recovery peak on May 22-24 was $\sim 4 \times 10^{-10} \text{ ergs cm}^{-2} \text{ s}^{-1}$. Taking into account the factor of ~ 1.6 decrease in visual luminosity indicated by the optical magnitudes measured near the times of the second peak and subsequent recovery maximum (Canizares, McClintock, and Grindlay 1979b) and using the observed reddening, the peak flux at wavelengths shortward of 3100 \AA was at least $6.5 \times 10^{-10} \text{ ergs cm}^{-2} \text{ s}^{-1}$. Neglecting interstellar extinction, the peak flux at longer wavelengths was $\sim 3.5 \times 10^{-10} \text{ ergs cm}^{-2} \text{ s}^{-1}$. This implies a value of $L_x/L_0 \approx 160$, similar to the values derived for other "soft" X-ray spectrum transients, including A1524-61, A0620-00, and H1705-25 ($L_x/L_0 \approx 200$, ~ 150 , and ~ 100 , respectively; Murdin et al. 1977; Griffiths et al. 1978), and for the 1978 March outburst of Aql X-1 ($L_x/L_0 \approx 200$; Charles et al. 1980). Canizares, McClintock, and Grindlay (1979b) estimate a value of $L_x/L_0 \sim 40$ using a slightly different X-ray spectrum, higher extinction, and an estimated bolometric correction.

Radio observations of a variable source consistent with the position of the Cen X-4 optical counterpart were obtained with the Very Large Array (Hjellming 1979). These measurements ($\nu = 4885$ MHz) show an initial detection of the source at a level of $\sim 3\text{mJy}$ on May 25, a peak flux of $\sim 8\text{mJy}$ on May 28, and a weak detection at the $\sim 1\text{mJy}$ level on June 2. As seen from Figure 1, these observations correspond roughly to the times of the commencement of the X-ray decline phase, the secondary recovery maximum (May 28-31), and subsequent decline. Clearly, a direct correlation of the X-ray and radio emission during this period may be ruled out. However, the approximate coincidence of the radio peak with the X-ray recovery maximum may reflect an underlying connection. The apparent lack of a direct correlation of the radio and X-ray fluxes is reminiscent of

an also apparently uncorrelated radio event ($\nu \sim 1400-2695$ MHz) observed from A0620-00 (Owen et al. 1976). In that case, the radio emission exhibited an approximately 6-fold decrease over a one week period immediately following the stage of X-ray maximum (corresponding X-ray decrease $< 25\%$; cf. Figure 1, Kaluzienski et al. 1977b). While the peak radio flux of the A0620-00 event was ~ 35 times greater than that of the present event, the X-ray/radio luminosity ratios (assuming roughly similar radio spectra) are comparable.

b. Transient Behavior

The existence of a class of sources whose X-ray emission is characterized by recurrent nova-like outbursts occurring at irregular intervals from months - years (e.g., Aql X-1, 4U1608-52, 4U1630-47, A0535+26, etc.) is now firmly established. Cen X-4 represents the first of the pre-Uhuru transient X-ray sources to be reobserved in outburst at X-ray wavelengths. The bright transient A0620-00/V616 Mon is similarly thought to recur on relatively long time scales based upon an observed optical brightening of that object ca. 1917 (Eachus, Wright, and Liller 1976). It is therefore likely that the majority of the transient X-ray sources exhibit recurrent X-ray outbursts at intervals short compared to stellar evolutionary time scales (i.e., average recurrence period $< T_{rec} > \lesssim 10^3$ yr.). Liller (1979) has noted the absence of earlier observed optical outbursts of Cen X-4 in a search of archival plates (limiting magnitude ~ 13.5 and 16.0 for the periods before and after 1900, respectively) dating back to 1889. However, in view of the irregular amplitude, duration, and flare recurrence interval characteristic of the shorter-period recurrent transients, this result probably does not represent a strong observational constraint on the prior source history. In fact, we note that if the apparent correlation of flare X-ray energy output with recurrence interval (viz., flare output \propto time since the last flare) observed in Aql X-1 (Kaluzienski, Holt, and Swank 1980) applies to Cen X-4 (and if no significant flares went undetected in the interim between the 1969 outburst

and the commencement of ASM sky coverage in 1974 October), the factor of ~ 20 difference in energy output of the 1969 and 1979 events implies that the previous outburst may have occurred as long as 200 years ago.

Based upon differ'ng sets of observational criteria, several authors have suggested that the transient X-ray sources may be differentiated into two distinct sub-classes. For example, Kaluzienski et al. (1977b; see also Kaluzienski 1977 and references therein) have proposed that source characteristics including peak X-ray flux, flare duration and decay time scale, X-ray spectrum, and spectral type of the optical counterpart serve to divide the observed sources into two general classes: bright, long-lived, soft spectral sources with late-type, low mass optical counterparts ("Type I") and weaker, shorter-duration, harder spectral sources identified with massive, early-type optical companions ("Type II"). In addition, Type II sources are typically characterized by X-ray pulsations indicative of a neutron star, while none of the Type I sources are observed to pulsate. In an alternative classification scheme, Cominsky et al. (1978) have suggested that the two source classes may be observationally differentiated primarily on the basis of the X-ray spectrum, with "soft" and "hard" transients characterized by effective continuum temperatures $kT \lesssim 7$ keV and $\gtrsim 15$ keV, respectively. In either classification scheme, the spectral hardness represents a definitive discriminator of the source type. We therefore adopt the designations "soft" and "hard" in lieu of the Type I/II terminology for denoting the two transient source subclasses throughout the remainder of this discussion.

The existing data on Cen X-4 is consistent with its classification as a soft transient. Notwithstanding the unusually short duration and steep initial decline of the present event, characteristics such as the amplitude of the outburst, the nature of the X-ray spectrum determined from the HAKUCHO data, and the X-ray to optical luminosity ratio support this classification. Also, Canizares, McClintock, and Grindlay (1979a,b) have noted the remarkable similarity of the spectrum

and nova-like variability of the optical counterpart to the archetypal soft transient A0620-00/V616 Mon. As discussed in the next section, the spectral type of the non-degenerate companion in Cen X-4 is probably that of a late-type dwarf. Finally, the X-ray characteristics of the 1969 outburst (amplitude, duration, decay constant, and spectrum; Evans, Belian, and Conner 1970) are consistent with the suggested source type. It is also clear, however, that the amplitude and duration of the X-ray outbursts may vary substantially among episodes. Thus, while the latter parameters may provide, on the average, an indication of the source type, they do not represent definitive class discriminators.

c. Short Time Scale Variability

Short-term features in the X-ray light curves of the transient sources have been interpreted by several authors as a reflection of the basic dynamic time scales of the optical companion and/or accretion disk. For example, the precursor emission peaks observed from a number of the soft transients have been explained in terms of various accretion-related effects occurring during the source turn-on (Stoeger 1976). Watson, Ricketts, and Griffiths (1978) have suggested that the pronounced double maximum observed in H1705-25 may be attributed to variations in the accretion rate arising within the accretion disk or at the inner Lagrangian point. The frequently observed recovery maxima have been interpreted as secondary episodes of mass exchange from the non-degenerate companion (Kaluzienski 1977). Strong evidence for prolonged mass exchange from the optical star is provided by the X-ray light curves of several transients (e.g., H1705-25, H1743-32, 4U1630-47) which have exhibited sustained emission for periods of \sim 1 year or longer following the initial outburst.

The suggested 8.2 hour X-ray modulation of Cen X-4 represents the second indication of a relatively short period modulation in a transient source. Evidence for an X-ray modulation at a period of \sim 1.3 days during the 1975 outburst of Aql X-1 has been reported by Watson (1976) and Kaluzienski et al. (1977a).

This effect was not detected in ASM observations of subsequent outbursts of that source (Charles et al. 1980), but might have gone undetected due to the limited instrumental sensitivity. The detection of a longer-period X-ray modulation ($P \sim 7.8$) was reported for A0620-00 (Matilsky et al. 1976) and supported by optical data (Duerbeck and Walter 1976; Chevalier, Illovaisky, and Mauder 1976), but was not evident in the ASM or Ariel 5 Sky Survey Instrument data (Kaluzienski et al. 1977b; Watson, Ricketts, and Griffiths 1978). Clearly, the reality of the various suggested periodicities and their possible identification with the system binary period should be viewed with caution.

The detection of an X-ray burst from Cen X-4 during the 1979 outburst confirms its association with the 10 minute burst-type event detected from within 1° of the source with the Vela satellites approximately 50 hours prior to the commencement of the 1969 outburst (Belian, Conner, and Evans 1972). The suggested association of the soft recurrent transient 4U1608-52 with the "Norma burster" (see Fabbiano et al. 1978 and references therein) was also confirmed recently by the combined results of HAKUCHO and the ASM when bursts were observed (Oda 1979a) concurrent with the onset of a transient episode in 1979 April (Kaluzienski and Holt 1979a). Thus, two of the coincidences between the soft transients and X-ray bursters argued by Fabbiano and Branduardi (1979) to be statistically significant are confirmed.

The bursts observed from Cen X-4 provide valuable information on this source. Oda (1979b; see also Matsuoka et al.) identified the recent burst as Type I (see Hoffman, Marshall, and Lewin 1978 for a discussion of burst classification) with a peak intensity $S \sim 25 S_{\text{crab}}$ (1.5-12 keV), a factor of ~ 6 greater than the peak outburst flux. The earlier burst attained a peak flux $S \sim 60 S_{\text{crab}}$ (3-12 keV), and the spectrum similarly exhibited noticeable softening during the decay (Belian, Conner, and Evans 1972). If we assume that the bursters constitute a physically similar class of objects and exhibit spherically symmetric emission with peak luminosities saturated at some limit, L_s , (in the thermonuclear

flash models (Woosley and Taam 1976; Joss 1977) L_s would be near the Eddington limit, L_E) the distance of Cen X-4 relative to those of other bursters can be estimated. Using a sample of ten bursters observed with SAS-3, and assuming these sources to be clustered around the galactic center at an average distance of ~ 9 kpc, Van Paradijs (1978, 1979) demonstrated that equating the observed peak burst luminosities to the Eddington limit for hydrogen accreting onto a $1.4 M_\odot$ object ($L_E \approx 1.8 \times 10^{38}$ ergs s $^{-1}$) implies a distance "correction factor" of ~ 1.3 (i.e., "true" distance ~ 1.3 times the "inferred" distance). Applying this procedure to the 1969 burst ($S \approx 1.4 \times 10^{-6}$ ergs cm $^{-2}$ s $^{-1}$) yields a source distance $d \approx 1.3$ kpc, with an uncertainty of at least 50% implied by the differing luminosities of the bursts. This distance implies peak outburst luminosities of $L_{\max} \approx 0.1 L_E$ and $\sim 0.6 L_E$ and corresponding total X-ray energy releases of $E_{\text{tot}} \approx 3 \times 10^{43}$ ergs and $\sim 6 \times 10^{44}$ ergs for the 1979 and 1969 outbursts, respectively.

IV. SOURCE MODELS

The detailed nature of the systems and the mechanisms underlying the outbursts of the soft transients have not been convincingly demonstrated. One class of models which is consistent with the collection of observational data invokes episodic mass exchange in a binary system composed of a late-type, low mass normal star and a collapsed companion (neutron star or black hole). Avni, Fabian, and Pringle (1976), for example, have interpreted A0620-00 in terms of an "X-ray dwarf nova" model, consisting of a red dwarf + neutron star (black hole) in a close binary system. The origin of the outbursts has generally been ascribed to the same mechanisms hypothesized in accretion models of the dwarf novae, i.e., episodic mass exchange arising from instabilities in the non-degenerate star (e.g., Bath et al. 1974) or in a quasi-stable accretion disk surrounding the compact companion (e.g., Osaki 1974). The former models have frequently invoked episodic Roche-lobe overflow as the mode of mass transfer (see, for example, Bath 1976 and references therein; Kaluzienski 1977; and Charles et al. 1980). Possible difficulties in the standard Roche model have been

pointed out for the soft transients A0620-00 (Oke 1977) and Aql X-1 (Margon, Katz, and Petro 1978), but Charles et al. (1980) argue on the basis of their observations of Aql X-1 that the non-degenerate star could be filling its Roche lobe after all.

It is therefore of interest to investigate the consistency of the Cen X-4 data with the standard semi-detached Roche model. For Cen X-4 the estimates of distance, quiescent magnitude, and extinction indicate an absolute visual magnitude $M_V \gtrsim 8$ (where the inequality refers to the uncertainty in optical magnitude), and a corresponding spectral class for a normal star later than $\sim K7$ with a mass $M_* \lesssim 0.6 M_\odot$ (Allen 1973). This implies a mass ratio $q \gtrsim 2.3$ ($M_X/1.4 M_\odot$), where, if the compact component is a neutron star (as the X-ray burst is thought to imply; see, for example, Lewin and Clark 1979), $M_X \lesssim 3 M_\odot$ (Arnett and Bowers 1977). Similarly, the presence of Cen X-4 in the Palomar Sky Survey indicates that $M_V \lesssim 11$ (assuming a plate limit of $m_V \sim 22$), implying a spectral class earlier than $\sim M5$, a mass $M_* \gtrsim 0.2 M_\odot$, and corresponding mass ratio $q \lesssim 7$ ($M_X/1.4 M_\odot$). The observed ratio of X-ray to optical flux represents a lower limit to the ratio of X-ray flux to the optical flux reprocessed by the hemisphere of the companion radiated by the X-ray source. As outlined by Charles et al. (1980) for Aql X-1, using the considerations of Chester (1979) and assuming the companion fills its Roche lobe, the standard semi-detached Roche model yields a range for the Cen X-4 mass ratio $7 \lesssim q \lesssim 45$, depending upon the orbital inclination (the lower and upper limits correspond to $i = 0$ and 90 degrees, respectively). If a disk dominates the optical emission, q would have to be larger, possibly implying that the star is within its Roche lobe. Alternatively, as pointed out by Charles et al., the star may be filling its Roche lobe but strongly shadowed by the disk. Given the uncertainties involved in determining the mass ratio, we consider the range of values implied by the X-ray to optical luminosity ratio reconcilable with a red dwarf of mass in the inferred range $M_* \sim 0.2 - 0.6 M_\odot$ and a neutron star companion. If the suggested 8.2 hour X-ray modulation is the binary period, it indicates independently

that the star, if normal, is close to filling its Roche lobe. For $q > 1.2$ the ratio of the stellar radius to that of its Roche lobe $\left(\frac{6.4}{P}\right)^{2/3} \frac{R_*}{R_\odot} \left(\frac{M_*/M_\odot}{M_\odot}\right)^{1/3}$ would range from 0.7 - 0.2, for spectral types K7-M5.

We note that the probability of observing eclipses in such a system would be significantly less than $\sim 20\%$ only if the companion were considerably later than K7. This would support the suggestion that the absence of eclipses in the soft transients may be indicative of an observational selection effect in which non-eclipsing systems are preferentially detected, either because the radiation flow from a disk is highly anisotropic (Milgrom 1978) or because an optically thick disk obscures the X-ray source in eclipsing systems (Jones and Raines 1979). Both models have the additional attractive properties of predicting a soft X-ray spectrum and the absence of pulsations due to the requirement of a weakly magnetic (i.e., $B \lesssim 10^{11}$ Gauss) neutron star as the accreting object. Finally, the observational selection effect in favor of relatively low inclination systems implied by these models could account for the lack of strong photometric modulation expected from X-ray heating of the stellar companion.

If the mass exchange occurs continuously from the non-degenerate star to a quasi-stable accretion disk with outbursts triggered by instabilities in the disk, constraints may be placed upon the mass leakage rate from the disk onto the neutron star (M_d) as a function of the star to disk exchange rate \dot{M}_{sd} . For Cen X-4, the ratio of the 1979 peak X-ray luminosity to quiescent luminosity ($L_{max}/L_q > 10^4$) and mean decay time (~ 2 weeks) imply $\dot{M}_d/\dot{M}_{sd} < .03$ during the 10 year interval since the preceding outburst. In the case of A0620-00 ($L_{max}/L_q > 10^5$, $\tau \sim 1$ month, and $\Delta T \sim 58$ years) the upper limit to this quantity is $\sim .006$. Interestingly, these limits are consistent with the values indicated for dwarf novae based upon the X-ray luminosities at minimum light of SS Cyg and U Gem (Swank et al. 1978).

An alternative model of the soft transients invoking unstable thermonuclear burning on an accreting neutron star has been proposed by Joss (1979), who suggested

the possibility that the outbursts represent carbon flashes occurring in an interior shell. The total X-ray energy released in the 1969 and 1979 outbursts are within the total available nuclear energy found possible ($\sim 10^{45}$ ergs) in this model. However, the amount of matter required for such an event to produce the 1979 outburst would have resulted in a steady accretion X-ray flux over the intervening 10 years of $S_q \sim 4 \times 10^{-10} \beta_A \beta_N^{-1}$ ergs $\text{cm}^{-2} \text{s}^{-1}$, where β_N and β_A are the mass to energy conversion efficiencies for carbon burning and accretion, respectively. Taking values of $\beta_A \sim .1$, and $\beta_N \lesssim 10^{-3}$, the resultant steady accretion flux would have been at a level of $\sim 30\%$ of the peak outburst flux. Clearly, steady accretion of the material required by the carbon flash model may be excluded by both the HEAO-A2 and ASM upper limits on the quiescent luminosity, unless the emission is somehow screened from the observer between outbursts (e.g., due to high optical thickness or geometrical beaming of radiation). Finally, the occurrence of the Type I burst observed with the HAKUCHO satellite subsequent to maximum light would be difficult to explain as a Helium flash if carbon burning were already proceeding. In fact, the occurrence of the burst after about 2.5×10^{43} ergs were released, if due to accretion, implies the accumulation of $\sim 5 \times 10^{22}$ gms of He (assuming cosmic abundances), on the order of that predicted for the production of Type I bursts in Helium flash models (Joss 1977, 1978; Lamb and Lamb 1978). However, the occurrence of the 10 minute event prior to the 1969 outburst and the occurrence of the 4U1608-52 bursts during onset of the 1979 April flare complicate the picture and even suggest that one may trigger the other. We do not know if any burst-like events occurred near the commencement of the 1979 outburst from Cen X-4. However, the upper limits on the quiescent flux would have allowed enough accretion to supply a Helium flash.

We conclude that the transient outbursts of Cen X-4 (and the soft transients in general) are most readily interpreted in terms of the standard accretion mechanism. Due to the relatively poor efficiency of thermonuclear burning and low elemental abundance, the carbon flash mechanism appears highly unlikely as

the cause of the outbursts. On the other hand, the supposed Helium flash occurred soon after enough material would have been accreted onto an $\sim 1.4 M_{\odot}$ neutron star. The optical observations and the suggested X-ray periodicity would imply a late-type, low mass optical companion within a factor of ~ 2 of filling its Roche lobe. The ratio of X-ray to optical luminosity could be consistent with such a model, whether or not a disk is present. More sensitive optical and X-ray observations during quiescence may be able to resolve the question of whether a substantial disk is built up between outbursts or whether the bulk of the mass exchange occurs only during the outburst itself.

ACKNOWLEDGMENTS

We are particularly indebted to Dr. M. Oda and the HAKUCHO observing team for communicating their X-ray observations prior to publication. We are likewise grateful to C. Wu for supplying details of the IUE observations. Finally, we thank Claude Canizares for an early pre-print of the optical results and Phil Charles for helpful discussions on the subject of the mass ratio.

REFERENCES

- Allen, C.W. 1973, Astrophysical Quantities (3rd Edition), Athlone Press, London.
- Arnett, W.D., and Bowers, R.L. 1977, Ap. J. Suppl., 33, 415.
- Avni, Y., Fabian, A.C., and Pringle, J.E. 1976, M.N.R.A.S., 175, 297.
- Bath, G.T., Evans, W.D., Papaloizou, J., and Pringle, J.E. 1976, M.N.R.A.S.,
169, 447.
- Bath, G.T. 1976, in Structure and Evolution of Close Binary Systems, Ed.
Eggleton, P., Mitton, S., and Whelan, J. (Rydel, Dordrecht), IAU
Symp. No. 73, 173.
- Belian, R.D., Conner, J.P., and Evans, W.D. 1972, Ap. J. (Letters), 171, L87.
- Canizares, C., McClintock, J., and Grindlay, J. 1979a, I.A.U. Circ., No. 3362.
- Canizares, C., McClintock, J., and Grindlay, J. 1979b, Ap. J. (Letters),
236, L55.
- Charles, P.A. et al. 1980, Ap. J., to be published in April 1 issue.
- Chester, T.J. 1979, Ap. J., 227, 569.
- Chevalier, C., Ilovaisky, S.A., and Mauder, H. 1976, I.A.U. Circ., No. 2957.
- Cominsky, L., Jones, C., Forman, W., and Tananbaum, H. 1978, Ap. J., 224, 46.
- Cowley, A.P., Crampton, D., and Hutchings, J.B. 1979, Ap. J., 231, 539.
- Duerbeck, H.W., and Walter, K. 1976, Astron. Astrophys., 48, 141.
- Eachus, L., Wright, E., and Liller, W. 1976, Ap. J. (Letters), 203, L17.
- Evans, W.D., Belian, R.D., and Conner, J.P. 1970, Ap. J. (Letters), 159, L57.
- Fabbiano, G., Bradt, H., Doxsey, R.E., Gursky, H., Schwartz, D.A., and
Schwarz, J. 1978, Ap. J. (Letters), 221, L49.
- Fabbiano, G., and Branduardi, G. 1979, Ap. J., 227, 294.
- Griffiths, R.E., Ricketts, M.J., and Cooke, B.A. 1976, M.N.R.A.S., 177, 429.

- Griffiths, R.E. et al. 1978, Ap. J. (Letters), 221, L63.
- Hjellming, R.M. 1979, I.A.U. Circ., No. 3369.
- Hoffman, J.A., Marshall, H.L., and Lewin, W.H.G. 1978, Nature, 271, 630.
- Holt, S.S. 1976, Ap. Space Sci., 42, 123.
- Holt, S.S., Kaluzienski, L.J., Boldt, E.A., and Serlemitsos, P.J. 1979, Ap. J., 233, 344.
- Jones, B.C., and Raine, D.J. 1979, Astron. Astrophys., 76, 179.
- Joss, P.C. 1977, Nature, 270, 310.
- Joss, P.C. 1978, Ap. J. (Letters), 225, L123.
- Joss, P.C. 1979, Comments on Astrophysics, 8, 109.
- Kaluzienski, L.J. 1977, Ph.D. Thesis, University of Maryland.
- Kaluzienski, L.J., Holt, S.S., Boldt, E.A., and Serlemitsos, P.J. 1977a, Nature, 265, 606.
- Kaluzienski, L.J., Holt, S.S., Boldt, E.A., and Serlemitsos, P.J. 1977b, Ap. J., 212, 203.
- Kaluzienski, L.J., Holt, S.S., and Swank, J.H. 1980, in preparation.
- Kaluzienski, L.J., and Holt, S.S. 1979a, I.A.U. Circ., No. 3349.
- Kaluzienski, L.J., and Holt, S.S. 1979b, I.A.U. Circ., No. 3360.
- Kaluzienski, L.J., and Holt, S.S. 1979c, I.A.U. Circ., No. 3362.
- Lamb, D.Q., and Lamb, F.K. 1978, Ap. J., 220, 291.
- Lewin, W.H.G., and Clark, G.W. 1979, Proc. of the Ninth Texas Symp., Ann. N.Y. Acad. Sci., in press.
- Liller, W. 1979, I.A.U. Circ., No. 3366.
- Margon, B., Katz, J.I., and Petro, L.D. 1978, Nature, 271, 633.
- Marshall, F. 1979, private communication.
- Matilsky, T. et al. 1976, Ap. J. (Letters), 210, L127.

- Matsuoka, M. et al. 1980, submitted to Ap. J. (Letters).
- Milgrom, M. 1978, Astron. Astrophys., 67, L25.
- Murdin, P., Griffiths, R.E., Pounds, K.A., Watson, M.G., and Longmore, A.J. 1977, M.N.R.A.S., 178, 27p.
- Oda, M. 1979a, I.A.U. Circ., No. 3349.
- Oda, M. 1979b, I.A.U. Circ., No. 3366.
- Oke, O.B. 1977, Ap. J., 217, 181.
- Osaki, Y. 1974, Publ. Astron. Soc. Japan, 26, 429.
- Owen, F.N., Balonek, T.J., Dickey, J., Terzian, Y., and Gottesman, S.T. 1976, Ap. J. (Letters), 203, L15.
- Seitzer, P., Smith, G., and Ross, B. 1979, I.A.U. Circ., No. 3372.
- Stoeger, W.R. 1976, Nature, 261, 211.
- Swank, J.H., Boldt, E.A., Holt, S.S., Rothschild, R.E., and Serlemitsos, P.J. 1978, Ap. J. (Letters), 226, L133.
- Terrell, J., Belian, R.D., Conner, J.P., and Evans, W.D. 1979, B.A.P.S., 24, 583.
- Van Paradijs, J. 1978, Nature, 274, 650.
- Van Paradijs, J. 1979, Ap. J., 234, 609.
- Watson, M.G. 1976, M.N.R.A.S., 176, 19p.
- Watson, M.G., Ricketts, M.J., and Griffiths, R.E. 1978, Ap. J. (Letters), 221, L69.
- Woosley, S.E., and Taam, R.E. 1976, Nature, 263, 101.
- Wu, C. 1979, talk presented at the 17th General Assembly of the IAU, Montreal.
- Wyckoff, S. 1979, I.A.U. Circ., No. 3386.

FIGURE CAPTIONS

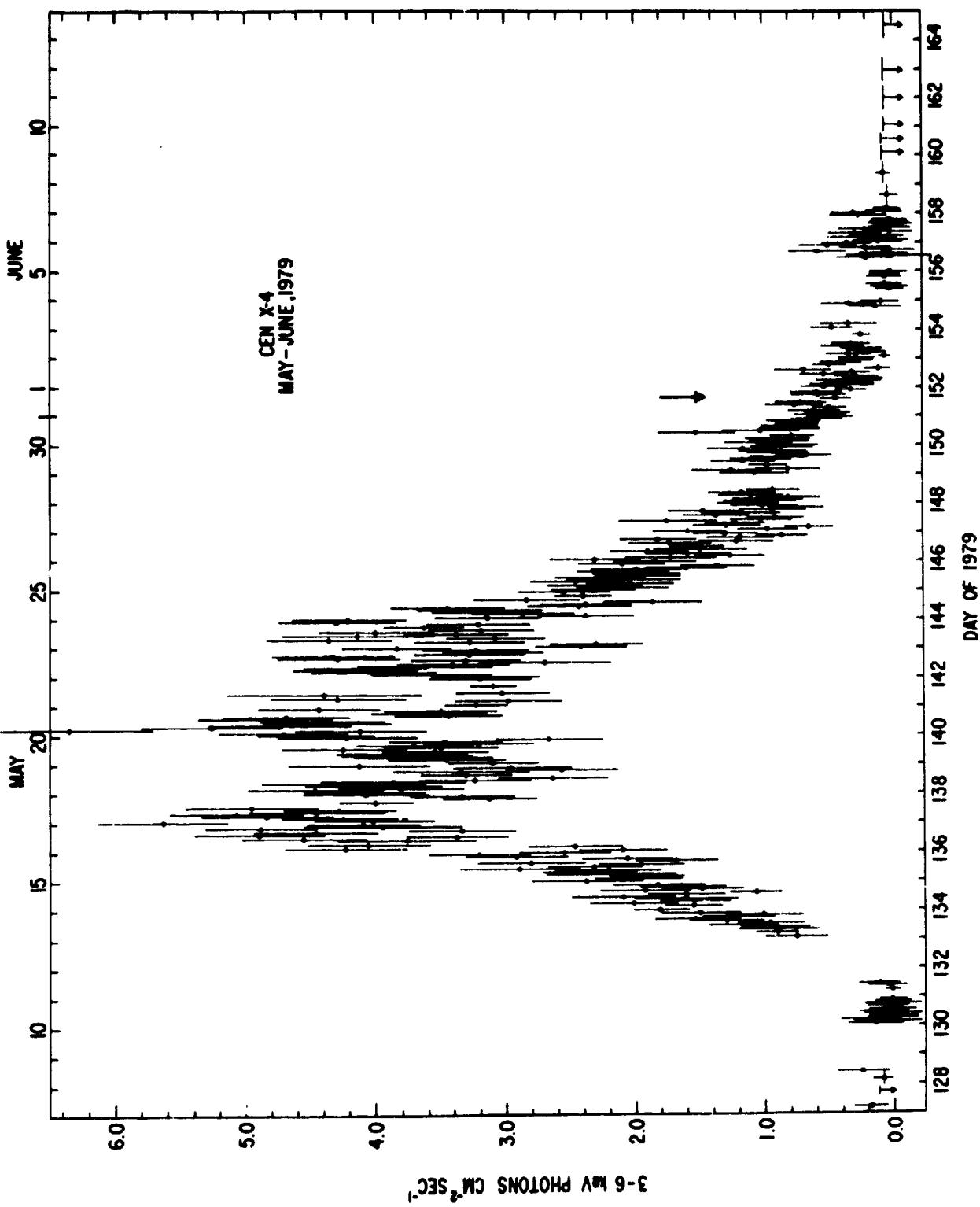
Figure 1 - ASM light curve of the 1979 outburst of Cen X-4. Points are effective incident 3 - 6 keV photon fluxes with corresponding $\pm \sigma$ statistical uncertainties. The data are predominantly single-orbit (~ 100 minute) integrations obtained in both the coarse and fine ($\delta\theta \sim 10^0$ and 2^0 , respectively) spatial resolution modes. The arrow (May 31) indicates the time of the X-ray burst reported by Oda (1979a).

Figure 2 - Plot of χ^2 versus folding period over the range $0.1 \leq P(d) \leq 1.5$. Histogram bins represent the average value of χ^2 (vs. the hypothesis of source constancy, $N = 7$ bins) over the corresponding period interval and have been adjusted to ensure adequate sampling resolution at the shortest periods. Arrows indicate the fundamental period of 0.3415^d and the $n = \frac{1}{2}, 2, 3$, and 4 harmonics.

Figure 3a - Detailed variation of χ^2 ($N = 7$ bins) in the vicinity of $P = 0.3415^d$. Solid lines indicate the approximate width of the χ^2 peak expected for a modulation at this period from a data sample of ~ 9 days.

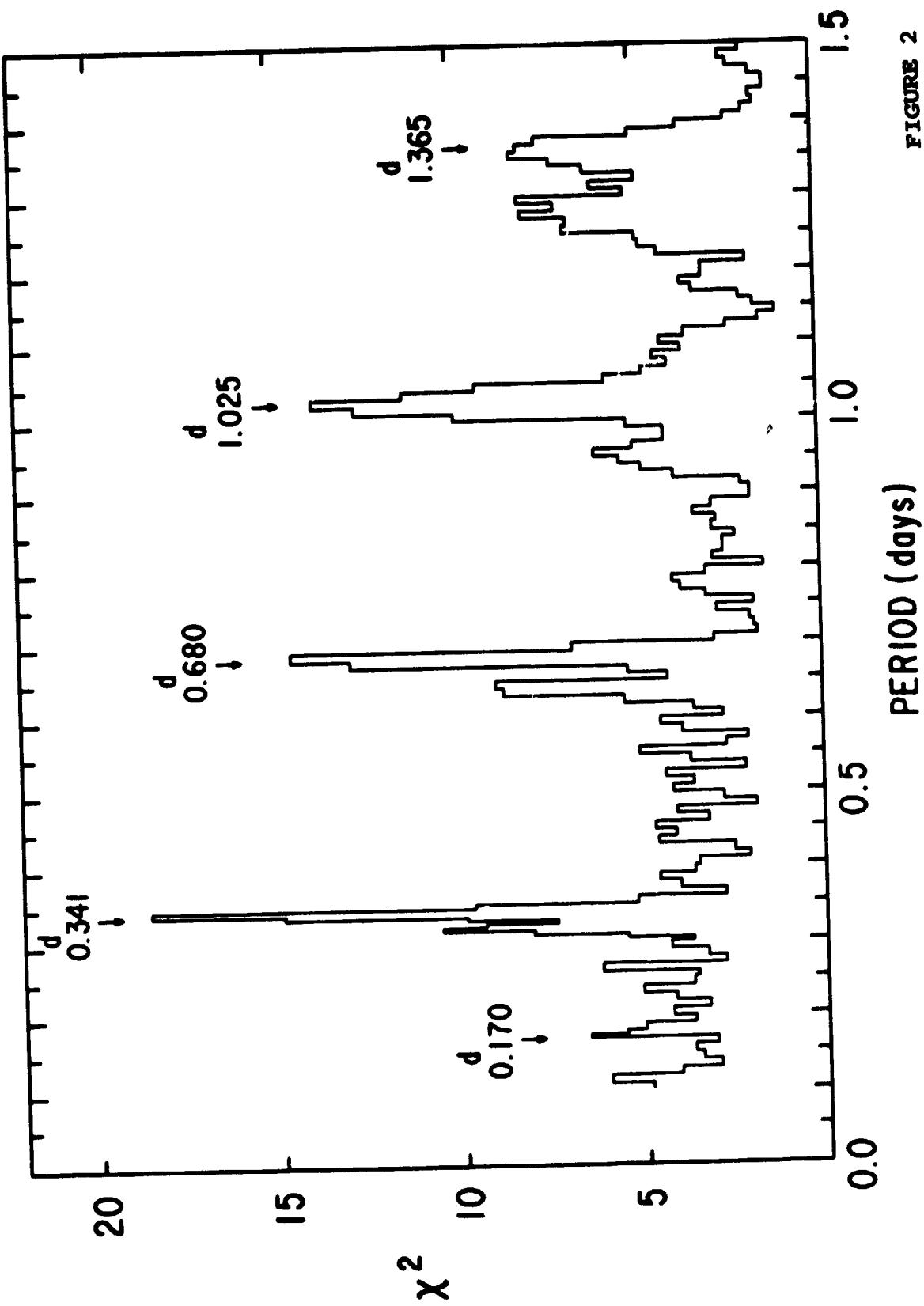
b - Folded light curve of the 0.3415^d modulation. The data have been folded in 14 bins at twice the fundamental period (0.683^d) to demonstrate the reproducability of the 0.3415^d effect over two independent data samples. The solid horizontal line represents the weighted average of the 105 data points used in the folding analysis.

FIGURE 1



ORIGINAL PAGE IS
OF POOR QUALITY

FIGURE 2



ORIGINAL PAGE IS
OF POOR QUALITY

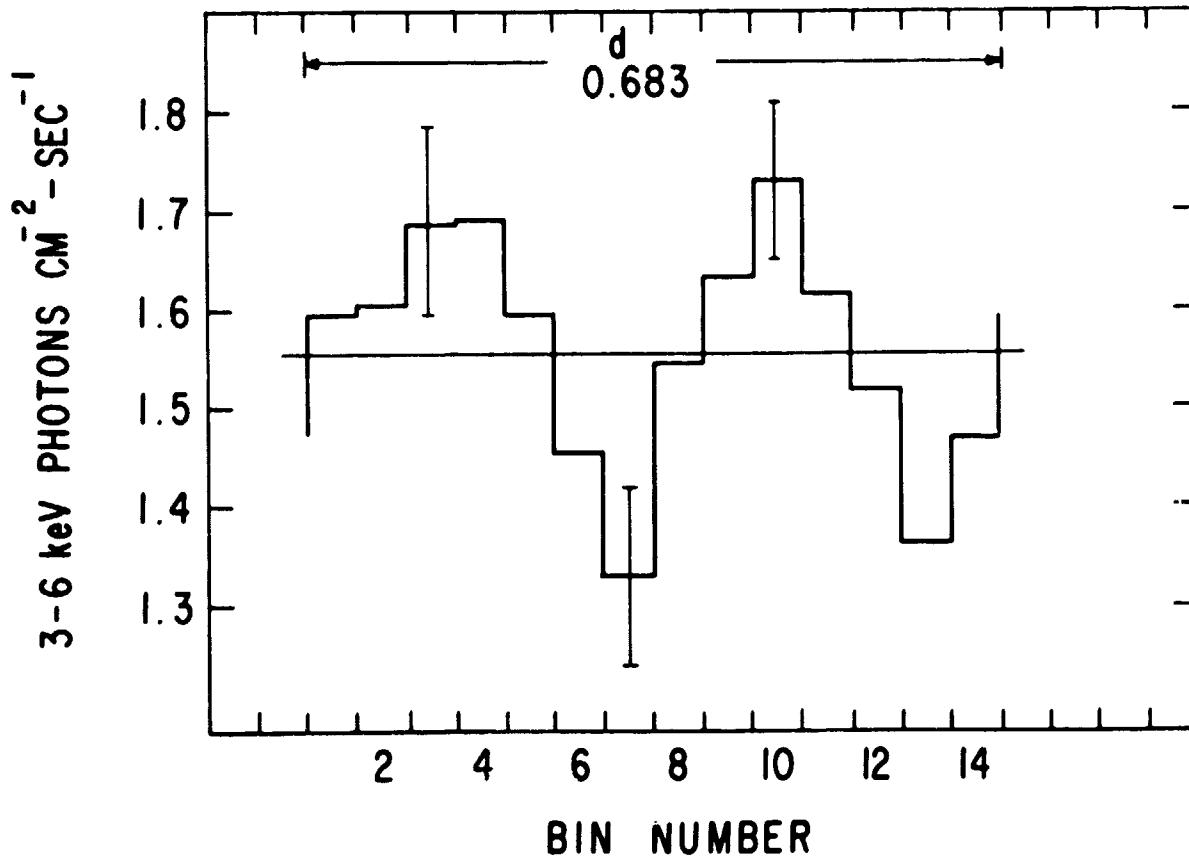
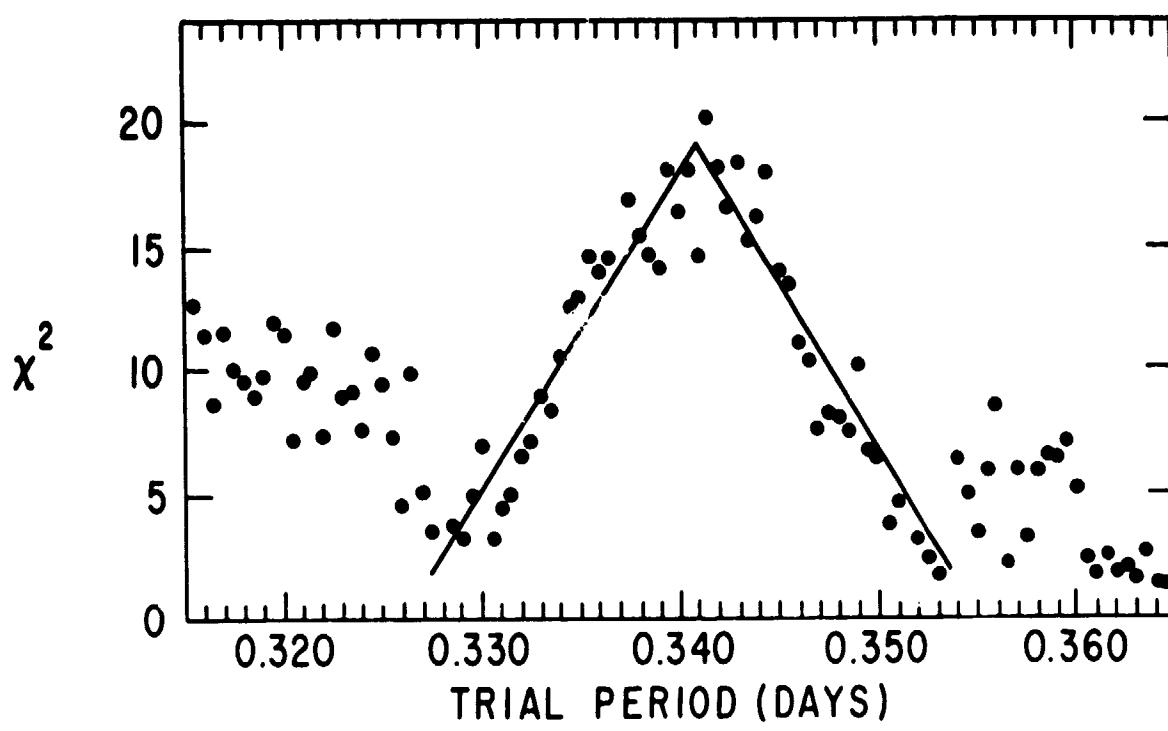


FIGURE 3

BIBLIOGRAPHIC DATA SHEET

1. Report No. TM 80694	2. Government Accession No.	3. Recipient's Catalog No.	
4. Title and Subtitle The 1979 X-Ray Outburst of Cen. X-4		5. Report Date May 1980	
7. Author(s) L.J. Kaluzienski, S.S. Holt, and J.H. Swank		6. Performing Organization Code 661	
8. Performing Organization Name and Address Code 661 Laboratory for High Energy Astrophysics NASA/Goddard Space Flight Center Greenbelt, Maryland 20771		9. Work Unit No.	
10. Contract or Grant No.		11. Type of Report and Period Covered	
12. Sponsoring Agency Name and Address		13. Sponsoring Agency Code	
15. Supplementary Notes Accepted for publication in Ap. J.			
16. Abstract In late spring 1979 the "classical" transient X-ray source Cen X-4 underwent its first major outburst since its initial discovery in 1979. We present X-ray observations of this event obtained with the Ariel 5 All-Sky Monitor. The flare light curve exhibits a double-peaked maximum at a level of ~ 4 times the Crab nebula, and its duration and characteristic decay time scale are the shortest yet observed from the class of "soft" X-ray transients. We estimate a total X-ray output of $\sim 3 \times 10^{43}$ ergs, a factor of ~ 20 less than that of the 1969 outburst. In addition, evidence is found for a regular modulation of the flux during the decline phase at a period of $8.2 + 0.2$ hours. The existing data are consistent with a source model involving episodic mass exchange from a late-type dwarf onto a neutron star companion in a relatively close binary system.			
17. Key Words (Selected by Author(s)) stars: binaries - stars: individual X-rays: binaries - X-Rays: bursts		18. Distribution Statement	
19. Security Classif. (of this report) U	20. Security Classif. (of this page) U	21. No. of Pages 25	22. Price*